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Project Description

WatchListR: a tool for developing watch-lists of invasive species to inform biosecurity decision-making

Philip J. Ivey[1], Katelyn T. Faulkner[2,3], Justin Miller[4], Clarke J.M. van Steenderen[1]

1 *Centre for Biological Control, Department of Zoology and Entomology, Rhodes University, Makhanda, South Africa*
2 *South African National Biodiversity Institute, Kirstenbosch Research Centre, Cape Town, 7735, South Africa*
3 *Department of Zoology and Entomology, University of Pretoria, Pretoria, 0028, South Africa*
4 *NCC Environmental Services (Pty) Ltd., 26 Bell Close, Westlake Business Park, Westlake, Cape Town, South Africa*

Corresponding author: Philip J. Ivey (p.ivey@ru.ac.za)

Abstract

The Global Biodiversity Framework calls for member countries to reduce the rate of introduction of known or potential invasive alien species by at least 50 percent by 2030. An essential tool that will assist countries in achieving this ambitious target is a list of known or potential invasive alien species that are absent from their territories but might enter along a variety of pathways ('watch-list' hereafter). Generating watch-lists requires consideration of curated information on a large number of species. The growing volume of distribution data and the improved understanding of historical species introductions and invasions have created a significant data overload for countries compiling watch-lists. We have developed a computational workflow to automate part of this process, enabling countries to draw up these lists quickly and cost-effectively. The *WatchListR* tool requires reliable and accurate information on species present in the country (indigenous and introduced, as well as economically important). As information on which species are present is sometimes not readily available, local experts should ideally review and verify the watch-lists developed by *WatchListR*. As a case study, we used *WatchListR* to develop a list of species prohibited for importation into the Republic of Mauritius. We explore the development of *WatchListR*, describe the processes used, consider the efficacy of the tool, highlight planned future advancements, and suggest how countries can support the tool's development through the use and creation of expert-validated watch-lists.

Key words: Biological invasions, border control, early detection, R environment, surveillance

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Introduction

Various types of alien species lists exist, each assisting to improve our knowledge and management of biological invasions. These include inventories of alien species that have been introduced (Pyšek et al. 2002, 2012; Zengeya et al. 2025); lists of species permitted for import (i.e., safe lists; Kumschick et al. 2024); and lists of species that are present and regulated (Wilson and Kumschick 2024).

Watch-lists are lists of alien species that are absent from the area of interest but that are likely to become invasive if introduced (referred to elsewhere as 'black list–warning lists' (Essl et al. 2011); 'warn lists' (Nehring and Klingenstein 2008); and 'alert lists' (Pili et al. 2024)). They are important tools that aid decision-making, resource prioritization, and the development of preventive strategies and contingency

plans (Vanderhoeven et al. 2015; Faulkner et al. 2017; Padayachee et al. 2019; Roy et al. 2019). For example, they can be used to direct surveillance towards high-risk species both at the border to prevent illegal, intentional, and accidental introductions (Faulkner et al. 2017) and post-border so that alien species can be managed soon after introduction (Vanderhoeven et al. 2015). As a real-world example of their utility, a ranked list of alien species likely to arrive, establish, and have an impact on biodiversity in Great Britain was published in 2014 (Roy et al. 2014), and within 2 years, seven of the top ten ranked species had been recorded in that region (Roy et al. 2019). These lists will be essential if the 196 countries that are party to the Convention on Biological Diversity are to meet Target 6 of the Kunming–Montreal Global Biodiversity Framework (https://www.cbd.int/gbf/targets/6), which requires them to prevent the introduction and establishment of priority invasive alien species and reduce rates of introduction by at least 50 percent by 2030.

Several methods have been developed to produce watch-lists (Roy et al. 2019), but generally they require the curation of various types of information for a large number of species, including information on invasion and impact history, distribution, introduction pathways, and the environmental suitability of the region of interest (for examples, see Vanderhoeven et al. 2015; Roy et al. 2019). Partly because of this, producing watch-lists can be time-consuming, data-intensive, and expensive, making it difficult for resource-poor countries to develop them (Faulkner et al. 2014). This issue has been compounded over the last decade as the amount of knowledge and readily accessible data on alien species and their distributions has increased dramatically. For example, in 2014 a watch-list was developed for South Africa (Faulkner et al. 2014) using an invasive species list derived from the Global Invasive Species Database (GISD) (Pagad et al. 2015) and occurrence data for these species from the Global Biodiversity Information Facility (GBIF). In the last decade more comprehensive, global invasive species datasets have been developed. For example, the Global Register of Introduced and Invasive Species (GRIIS) (Pagad et al. 2022), and data from various new sources, like iNaturalist, have been increasingly incorporated into GBIF. This means that if the method used to develop the watch-list for South Africa was implemented today, it would be derived from a list that includes ~24,000 alien species (based on GRIIS), 27 times the number of species in the GISD (884 species) in 2014, and over 3 billion occurrence records from GBIF, a six-fold increase on the number available in 2014 (500 million records, https://www.gbif.org/analytics/global). Therefore, although simple, rapid watch-list methods have been developed specifically to meet the needs of resource-poor countries (e.g., Faulkner et al. 2014), the increase in both invasive species data and distribution data means that a computational tool is required to effectively manage and process these data to produce watch-lists.

In response to this challenge, we developed novel software, *WatchListR*, to automate part of the process. The software follows similar steps to the Faulkner et al. (2014) watch-list approach but uses tools that can manage the large amounts of data effectively and cost-efficiently. Here we describe the software and detail its implementation using the Republic of Mauritius as a case study.

Methods and software

WatchListR comprises Linux and R scripts that use a global list of terrestrial and freshwater invasive species names from the GRIIS database. Faulkner et al. (2014) is a multi-taxon watch-list procedure, and thus the GRIIS was selected over other

open-access lists of invasive species (e.g., Dyer et al. 2017; van Kleunen et al. 2019; Biancolini et al. 2021), as it provides information on invasive species from a wide range of taxonomic groups (Pagad et al. 2022). These invasive species names are used to query the GBIF Backbone Taxonomy, which integrates all name-based information into unique identifiers, such as GBIF Species Keys. Since all taxonomic synonyms share the same Species Key under a single accepted scientific name, this process ensures that all records are correctly tallied to the same taxon. These unique Species Keys are subsequently used by *WatchListR* to search the GBIF database for all available records with coordinates. From GBIF, only the Species Keys, synonym status, and coordinates are utilized, with the latter used to assign each record to the Köppen-Geiger (KG) climate zone into which it falls, allowing for broad-scale climate matching. Broad-scale KG climate matching compares the target country's climate zones with those in which each invasive species is known to occur, identifying and listing species from similar climates to those in the target country. The software requires the following inputs: (1) a list of invasive terrestrial and freshwater species (obtained from GRIIS) for one kingdom at a time, and (2) lists of species that are already present in the country. An optional input is a list of high-risk countries that are likely to be sources of invasive species (e.g., regular trading partners). The summary below and Fig. 1 describe each of the steps in the process.

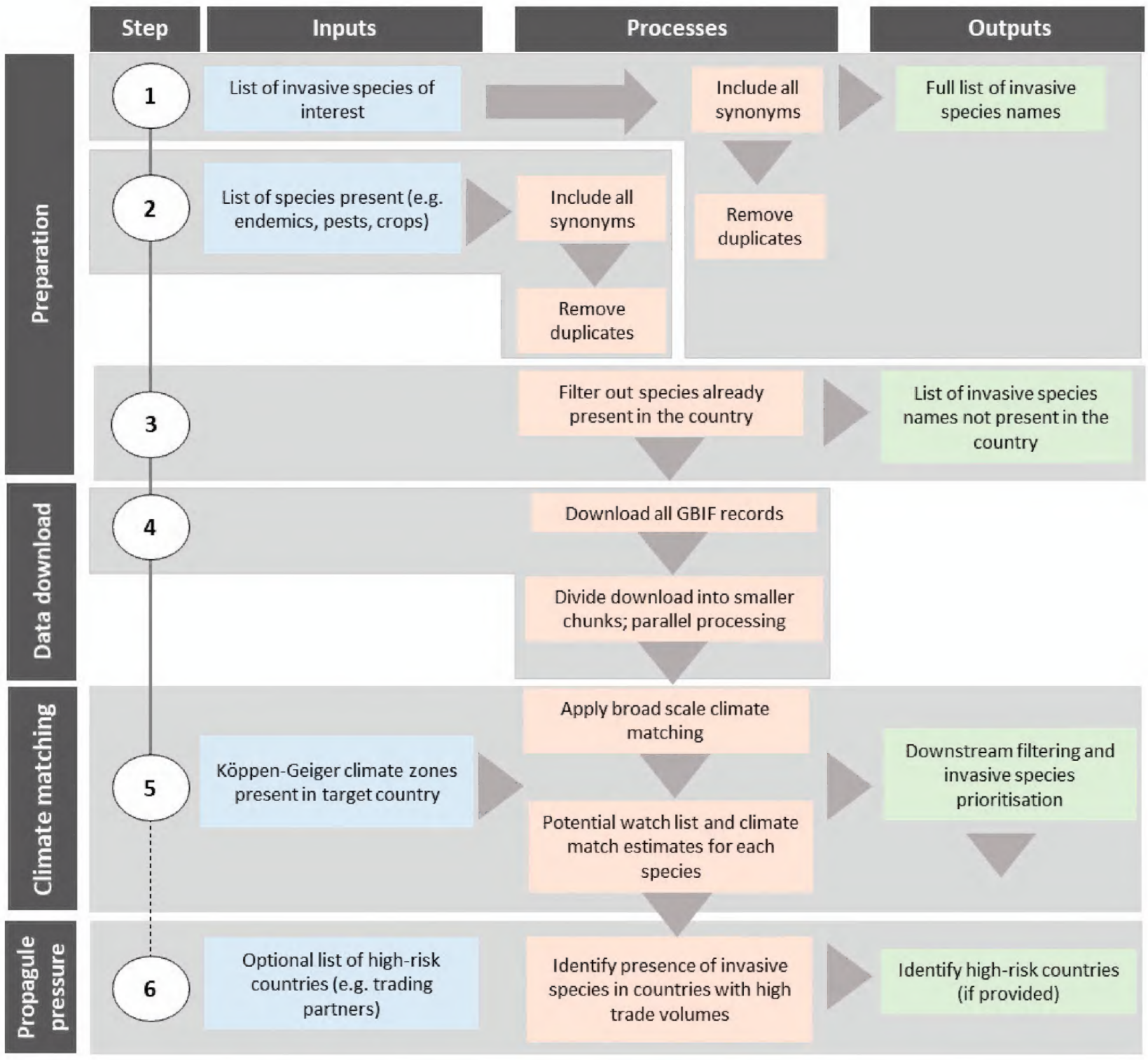
Step
Inputs
Processes
Outputs
Preparation
1
List of invasive species of interest
Include all synonyms
Full list of invasive species names
2
List of species present (e.g. endemics, pests, crops)
Include all synonyms
Remove duplicates
Remove duplicates
3
Filter out species already present in the country
List of invasive species names not present in the country
Data download
4
Download all GBIF records
Divide download into smaller chunks; parallel processing
Climate matching
5
Köppen-Geiger climate zones present in target country
Apply broad scale climate matching
Potential watch list and climate match estimates for each species
Downstream filtering and invasive species prioritisation
Propagule pressure
6
Optional list of high-risk countries (e.g. trading partners)
Identify presence of invasive species in countries with high trade volumes
Identify high-risk countries (if provided)

Figure 1. Flow diagram describing the data inputs, flow of work, and outputs from the watch-list development.

Step 1: Preparation of a list of invasive species

WatchListR takes the inputs of invasive terrestrial and freshwater species of interest from GRIIS and obtains taxonomic synonym data from the GBIF taxonomic backbone (https://www.gbif.org/dataset/d7dddbf4-2cf0-4f39-9b2a-bb099caae36c) to ensure that the process assesses all available content (Box 1). This search is carried out through the use of the *name_backbone_checklist()* function in the *rgbif* package (Chamberlain et al. 2024). At the end of Step 1, *WatchListR* produces a list of unique invasive species names, with accompanying information assigning each as the "accepted" name or a "synonym" under a designated GBIF Species Key.

Box 1. The issue with taxonomic synonyms.

Synonyms for accepted species names and taxonomic homonyms (taxon names that are spelled the same but belong to different species) are major caveats to searching for records on a public database such as GBIF. For example, a search on the Royal Botanic Gardens, Kew Plants of the World Online database for the cactus *Opuntia maxima* returns the full accepted name (*Opuntia maxima* Mill.) and 18 synonyms (https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:136788-1#synonyms). A GBIF search for *Opuntia maxima* (https://www.gbif.org/search?q=Opuntia%20maxima) currently reveals three separate listings, each with a different authority (*Opuntia maxima* Mill.; *Opuntia maxima* Salm-Dyck; and *Opuntia maxima* Salm-Dyck ex DC.), with two of these names (*Opuntia maxima* Salm-Dyck and *Opuntia maxima* Salm-Dyck ex DC.) being synonyms of *Opuntia ficus-indica* (L.) Mill. To deal with these issues, *WatchListR* searches the GBIF taxonomic backbone for each input species name – on both the invasive species list and the list of species already present in the target country – for synonyms. Both accepted species names and their synonyms are included in a collated list that is used for subsequent processing. GBIF records are downloaded for each unique Species Key, under which all synonyms are grouped. Final taxon names are recorded according to the current accepted name.

The GBIF output is shown below for a GBIF Backbone Taxonomy search of *Opuntia maxima* and *Opuntia ficus-indica*, which illustrates that:

• The entry for *Opuntia maxima* Salm-Dyck is identified as a SYNONYM whose currently ACCEPTED name is *Opuntia ficus-indica* (L.) Mill. As a result, both of these entries share the same Species Key: **5384064**.

• The second entry, *Opuntia maxima* Mill., represents a separate ACCEPTED taxon (a homonym of *Opuntia maxima* Salm-Dyck) and is correctly distinguished by a unique Species Key: **5626003**. This process ensures that records submitted under different names are tallied to the correct species.

Scientific name	Status	Match type	Canonical name	Rank	Species	Species key	Num. recs	Original input
***Opuntia ficus-indica* (L.) Mill.**	ACCEPTED	EXACT	*Opuntia ficus-indica*	SPECIES	*Opuntia ficus-indica*	**5384064**	27630	*Opuntia ficus-indica*
***Opuntia maxima* Mill**	ACCEPTED	EXACT	*Opuntia maxima*	SPECIES	*Opuntia maxima*	5626003	1380	*Opuntia maxima*
***Opuntia maxima* Salm-Dyck**	SYNONYM	EXACT	*Opuntia maxima*	SPECIES	*Opuntia ficus-indica*	**5384064**	27630	*Opuntia maxima*

Step 2: Preparation of a list of species that are present

WatchListR takes the lists of species already present in the country and follows similar processes to Step 1, obtaining taxonomic synonym data to access all relevant content. Species already present could include endemics, agricultural species, or invasive species that have already entered the country. A full list of names (accepted names and synonyms) of species present in the country is produced.

Step 3: Creation of a list of species that are absent

WatchListR processes the outputs from the first two steps by removing species already recorded in the country from the complete list of invasive species. This results in a list of invasive species that are not yet present, or not yet documented, in the country (Fig. 1).

Step 4: Download of occurrence records

WatchListR downloads all the available GBIF records for each of the invasive species that are absent from the country, using the procured Species Keys. GBIF records are downloaded using the *occ_download()* function from the *rgbif* R package, where the user's valid GBIF credentials are required. Records with geospatial issues or missing coordinates, as well as those originating from zoos, botanical gardens, or fossil records, are excluded from the search.

Step 5: Climate matching

WatchListR automatically detects the KG climate zones present in the target country (Beck et al. 2018; https://www.gloh2o.org/koppen/) and assigns the appropriate KG zone to the coordinates for every invasive species record sourced from GBIF. The analysis then conducts broad-scale climate matching by comparing the KG climate zones present in the target country to those in which each invasive species is known to occur. To efficiently manage the large quantity of distribution data, we used a data-partitioning processing approach, whereby the dataset was divided into smaller subsets, processed in parallel, and subsequently merged to obtain the final output. For each species, the software records the (1) total number of occurrence records; (2) cumulative number and proportion of records occurring within all KG zones that exist in the target country; (3) cumulative number and proportion of records in each KG zone that exists in the country; and (4) cumulative number and proportion of records found in the country. The output is a potential watch-list of invasive species not present in the country but present in areas with similar climates.

Step 6: Propagule pressure (optional)

In Step 6, *WatchListR* identifies countries with high climatic similarity. Using trade and tourism data from global datasets (https://www.fao.org/faostat/en/#home; https://comtradeplus.un.org/) and country-specific trade data (Statistics Mauritius 2025), one can identify which countries with high climatic similarity also have high trade volumes with the target country. *WatchListR* can calculate the number and proportion of records from each of the high-risk countries if a list of those countries is provided. Countries regarded as high risk are those that have high trade volumes (contributing 5 percent or more of the value of goods imported), have similar climate zones to those of the focal country (one or more of the KG zones are present in both countries), and have distribution records showing the presence of a moderate to high number (20 or more) of known invasive species. Assessing the likelihood of potential invasive species arriving from a country with a similar climate can assist efforts to prevent the introduction of those species. The user needs to provide a list of country codes (e.g., India = IN, South Africa = ZA) (based on ISO3166, accessible at https://www.iso.org/iso-3166-country-codes.html; https://www.iban.com/country-codes) of interest, and these will be included in the final watch-list output.

The full *WatchListR* analysis for an invasive species list comprising approximately 4,000 taxa takes under 2 hours to complete. The analysis for Mauritius (presented below) was performed on the Centre for High Performance Computing (CHPC) Lengau Cluster (https://www.chpc.ac.za/). Each job was submitted to

the "serial" queue and utilized the resources of one compute node, employing 23 CPUs (cores) to execute the tasks.

An R Shiny (Chang et al. 2025) dashboard accompanies *WatchListR* (https://clarkevansteenderen.shinyapps.io/watchlistR/) for user-friendly downstream charts and the automated creation of required input files. The dashboard allows end-users to upload their final watch-list via a graphical user interface (GUI), produce summary graphics, and filter the data to their specifications.

Case study

Good biosecurity relies on good knowledge of what species are already present in the country and clear motivations as to why authorities want to prevent the entry of specific alien species. The United Nations Development Programme contracted NCC Environmental Services, South Africa, to support the Republic of Mauritius in building the island nation's biosecurity capacity. The Centre for Biological Control at Rhodes University, South Africa, was part of the NCC Environmental Services team and oversaw the process to prepare an appropriate watch-list. Ivey et al. (in prep.) describe the context, stakeholder engagement, and process followed to develop the watch-list for the Republic of Mauritius. In the Republic of Mauritius, the National Invasive Alien Species Committee has the legal mandate to compile a watch-list of alien species. Relevant government departments and stakeholders are represented on this committee, which can facilitate the gathering of lists of species, including agricultural pests, economically important plant species, invasive alien species present in the country, and others. The support of representatives of this committee was essential in gathering the necessary data for *WatchListR* to compile the watch-list.

For this case study, we used *WatchListR* to develop a watch-list of terrestrial and freshwater plants and animals and did not consider marine species (the Köppen–Geiger climate zones cannot be used for marine species) nor organisms from kingdoms such as fungi, bacteria, and viruses. To protect and promote plant and animal health (particularly critically endangered plant species), it is important that the watch-list include all plant and animal pathogens. A plant disease could drive rare plants to extinction if permitted to enter the Republic of Mauritius.

Table 1 gives the results of the analysis undertaken by *WatchListR* for the Republic of Mauritius. For plants, we considered 11,114 records listed on the GRIIS database. GRIIS provides checklists of introduced (naturalized) and invasive alien species that are present in specified geographic units (mostly countries, but also islands, offshore territories, and protected areas) (Pagad et al. 2022). Therefore, many of the species are recorded multiple times on the register, and these duplicates were filtered so each species is listed only once. The Republic of Mauritius records 40 plant species on GRIIS. After consolidating the list and removing indigenous and introduced species already present in the Republic of Mauritius, the list contained 2,481 invasive plant species. Following the previously described filtering steps and synonym searches, the list grew to 3,229 species names, which were used to obtain GBIF records (GBIF 2025a). As outlined in Step 1 in the software methodology, all taxonomic synonyms were grouped under single unique GBIF Species Keys. Similarly, cases of homonyms were dealt with through the use of distinct Species Keys, despite identical species names (see Box 1). This GBIF search yielded a total of 162,603,988 distribution records, which were considered for climate matching to the three climate zones present in the Republic of Mauritius (Fig. 2). A total of

Table 1. The steps in the implementation of the *WatchListR* pipeline, materials or techniques used, and the number of species at each step.

Step		Materials or techniques	Number		
				Plants	Animals
1.	Preparation of a list of invasive species	- Global Register of Introduced and Invasive Species (GRIIS)	Total number of records on the GRIIS list	11114	2242
			Taxa in GRIIS that are not included in the GRIIS Republic of Mauritius	3221	745
2.	Preparation of a list of species that are present	- Global Biodiversity Information Facility and other references	Taxa listed as present in the Republic of Mauritius were removed from the list	740	23
3.	Creation of a list of species that are absent		Taxa listed as invasive and absent from the Republic of Mauritius	2481	722
4.	Download of occurrence records	*WatchListR* downloaded data for: - For terrestrial and freshwater species - Köppen–Geiger (KG) climate classification maps. - Global Biodiversity Information Facility	Result of synonym search of list above Serves as input list for GBIF search	3229	705
			GBIF records	162,603,988	137,360,927
			Data subsets of ~2 million records	82	69
5.	Climate matching	- After climate matching to the Köppen–Geiger zones of Mauritius, the final list	Full list	2902	680
			>1000 records on GBIF	1868	374
			>1000 records and 40% climate match	328	188
6.	Propagule pressure (optional)	- Trade data Republic of Mauritius - Information on tourists - The analysis included assessment of species presence in India, China, South Africa, Malaysia, the United Arab Emirates, France, Indonesia, and Kenya as "high-risk" countries	Number of taxa present in trading partner		
			India (Tourism and Trade)	68	20
			China (Trade)	79	27
			South Africa (Tourism)	63	5
			Malaysia (Trade)	47	19
			Arab Emirates (Tourism)	0	0
			France (Tourism)	22	5
			Indonesia (Trade)	63	18
			Kenya (Trade and Tourism)	3	3

2,902 plant taxa were found to occur in climate zones that are found in the Republic of Mauritius. These 2,902 plant taxa could all pose an invasion threat to the Republic of Mauritius, but this is too large a list for planning and executing meaningful biosecurity measures. Of these, 1,868 had >1,000 distribution records (likely to be widely invasive and thus have high propagule pressure), of which 328 had more than 40% of their records occurring within one of the three KG zones that exist in the Republic of Mauritius. We recommend that all 2,902 taxa of plants be on the watch-list. The aforementioned 328 taxa should be the focus of biosecurity efforts, as currently they are the most widely recorded species and thus are considered likely to be introduced, and as greater than 40% of their records occur in a similar climate zone, they are likely to establish in the Republic of Mauritius, if introduced. In order to further assist biosecurity efforts, we produced, through *WatchListR*, an assessment of the presence of these plant species in India, China, South Africa, Malaysia, the United Arab Emirates, France, Indonesia, and Kenya, as these are countries with which the Republic of Mauritius has a high proportion of trade and tourism (Ivey et al. in prep.). Between 45 and 80 of these plant species occur in

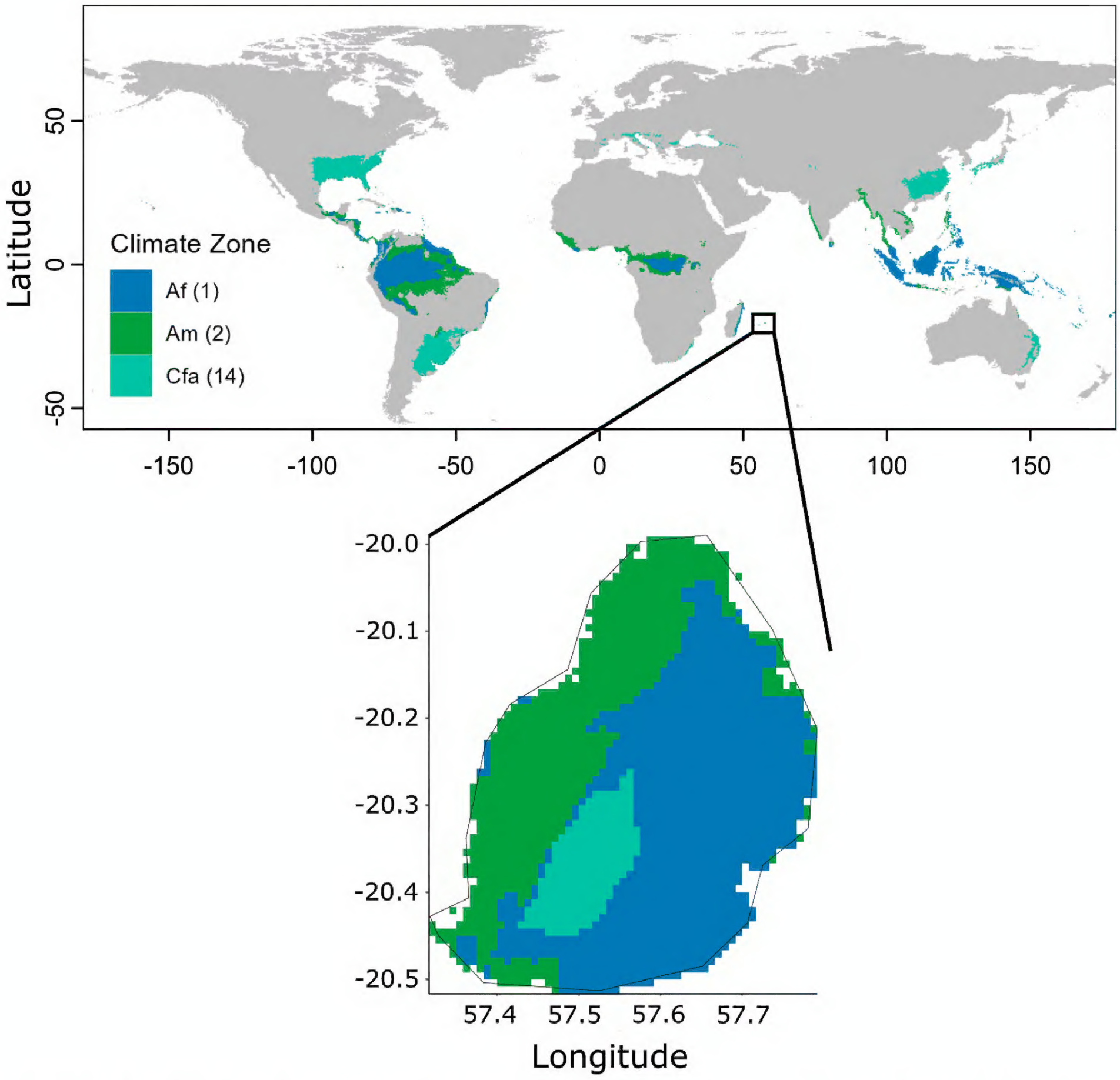

Figure 2. Köppen–Geiger climate zones (Beck et al. 2018) at a global scale that are shared with Mauritius (inset), used for broad-scale matching in *WatchListR*. Köppen–Geiger maps for available target countries can be created in the associated R Shiny application.

these countries (China (79 species), India (68 species), Indonesia and South Africa (both 63 species), and Malaysia (47 species)), suggesting that to prevent the introduction of these species, it would be important to have surveillance of cargo and transport vessels (e.g., ships, planes) from ports of origin in these countries.

For animals, we considered 2,242 records listed on the GRIIS database. After removing 23 indigenous and introduced species already present in the Republic of Mauritius, the list contained 722 invasive animal species. Following filtering and synonym searches, the list was reduced to 705 species, which was used as the input list for accessing GBIF records (GBIF 2025b). This GBIF search yielded a total of 137,360,927 distribution records, which were considered for climate matching. A total of 680 invasive animal taxa were found to occur in the climatic zones found in Mauritius (Table 1). While this is an order of magnitude fewer than the number of plant species, it is a relatively large number for biosecurity officials to consider.

By only considering those species with >1,000 distribution records and greater than 40% of records in the climate zones found in Mauritius, the number of species on the list was reduced to 188 (Table 1, and Figs 3, 4). Biosecurity officials should focus attention on imports from China, India, Malaysia, and Indonesia, where 27, 20, 19, and 18 of these animal species occur, respectively (Table 1).

In order to assist biosecurity officials in their efforts to prevent alien and potentially invasive species from entering the Republic of Mauritius, *WatchListR* can provide information on species that are present in countries responsible for high levels of imports. Figs 3, 4, respectively, identify plant and animal species that might be more likely to be introduced, as they occur in sufficiently high levels (number of records) in China, India, Indonesia, and Malaysia. Six plant species – *Hellenia speciosa*, *Muntingia calabura*, *Oldenlandia corymbosa*, *Pteris vittata*, *Sieruela rutidosperma*, and *Sphagneticola trilobata* – occur in three or four of these countries (Fig. 3). This might suggest there is a greater risk of these species arriving in the Republic of Mauritius due to the high and increasing levels of trade. Likewise, the Asian common toad (*Duttaphrynus melanostictus*) and the Asian honey bee (*Apis cerana*) are identified as present in all four of these countries (Fig. 4). Biosecurity officials could be encouraged to pay particular attention to pathways along which these species might be transported.

Discussion

It is well established that well-planned biosecurity that focuses on preventing the movement of species along human-mediated routes can effectively and relatively cheaply reduce the spread of invasive species (IPBES 2023). Currently, there are instances when only insufficient or skewed data are available to those who make decisions about the management of biological invasions and biosecurity (IPBES 2023). Biosecurity officials can use watch-lists as a valuable tool, especially if they can be developed relatively inexpensively for poorer regions (Faulkner et al. 2014). A watch-list that identifies species that are invasive elsewhere, are present in regions with similar climatic conditions to those of the focal country, and, if introduced to the focal country, will likely become invasive, is invaluable. Knowledge of which potentially invasive species are likely to come from which country, and along which pathway, is important for planning biosecurity operations (IPBES 2023). The GRIIS database provides much larger amounts of data and is more comprehensive than the GISD. GRIIS provides information on introduced and invasive species (Pagad et al. 2022). Even though the GRIIS provides a great deal of data, collection of this data is skewed towards countries that are better informed and resourced to gather the data for their territories. Likewise, access to data from community science platforms such as iNaturalist provides huge numbers of records to consider when mapping species distributions, but this data is not without biases (Di Cecco et al. 2021; Geurts et al. 2023). The *WatchListR* pipeline, including the R Shiny dashboard, is freely available on GitHub (https://github.com/clarkevansteenderen/KG_watchlist_parallel/tree/main), with step-by-step instructions for its deployment. The Centre for Biological Control at Rhodes University (https://www.ru.ac.za/centreforbiologicalcontrol/) and NCC Environmental Services can be contacted to assist in facilitating the implementation of *WatchListR*, helping countries to compile a watch-list of invasive species, and supporting biosecurity officials in preventing invasive species introductions.

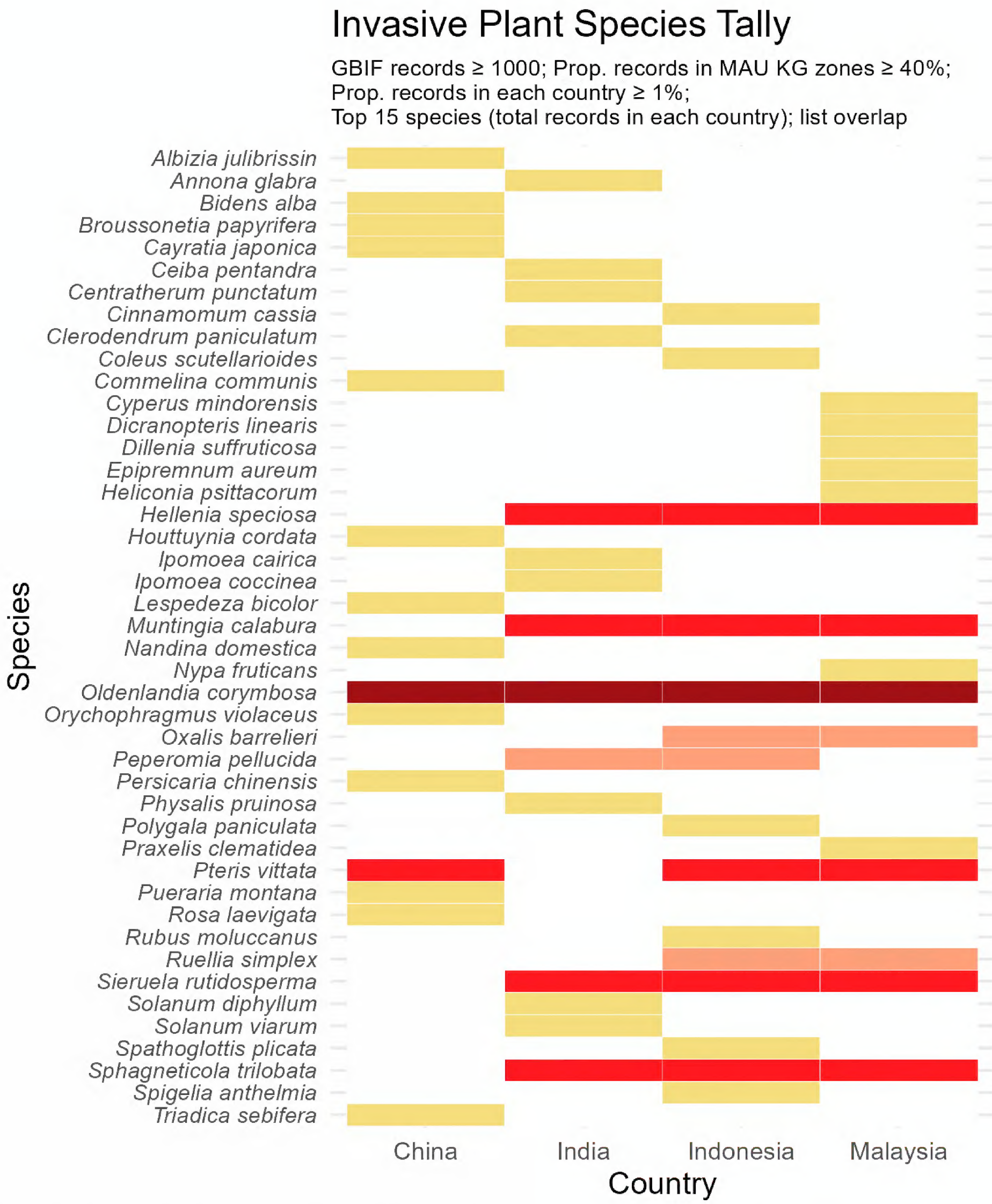

Figure 3. Presence of plant species on the recommended watch-lists in countries with high and growing levels of trade with the Republic of Mauritius (MAU). Biosecurity officials might be more vigilant of species from these countries. Stripe colors indicate the number of countries in which the species are found: beige = 1 country, salmon pink = 2 countries, red = 3 countries, and brown = 4 countries.

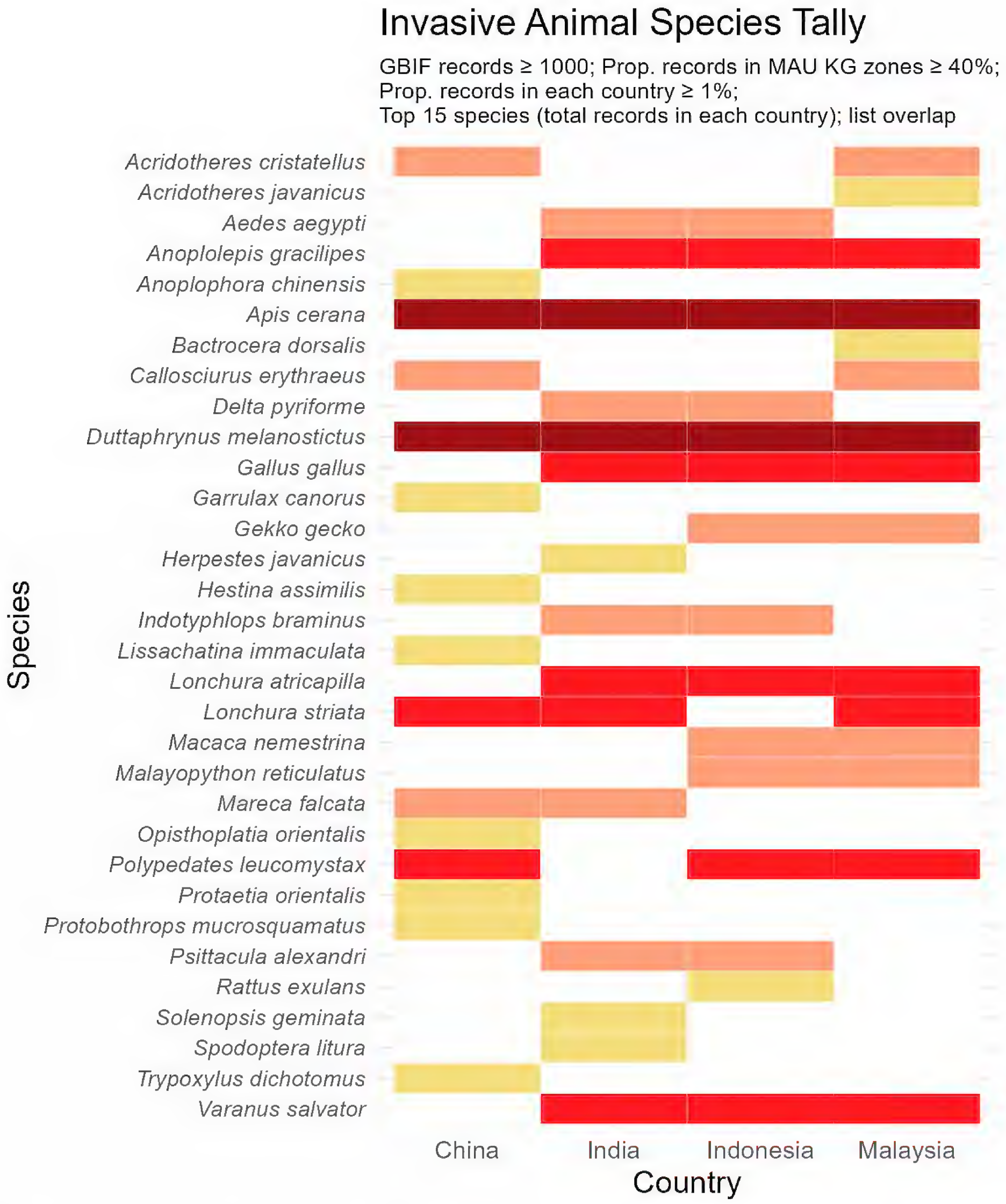

Figure 4. Presence of animal species on the recommended watch-lists in countries with high and growing levels of trade with the Republic of Mauritius. Biosecurity officials might be more vigilant of species from these countries. Stripe colors indicate the number of countries in which the species are found: beige = 1 country, salmon pink = 2 countries, red = 3 countries, and brown = 4 countries.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

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Author contributions

Conceptualization: KTF, CJMvS, PJI, JM. Data curation: CJMvS, PJI. Formal analysis: KTF. Funding acquisition: JM. Investigation: KTF, PJI. Methodology: CJMvS, KTF, PJI. Project administration: JM, PJI. Software: CJMvS. Writing – original draft: PJI, KTF. Writing – review and editing: JM, PJI, CJMvS, KTF.

Author ORCIDs

Philip J. Ivey https://orcid.org/0000-0003-1712-7481
Katelyn T. Faulkner https://orcid.org/0000-0002-3955-353X
Clarke J.M. van Steenderen https://orcid.org/0000-0002-4219-446X

Data availability

All of the data that support the findings of this study are available in the main text. GitHub repository: https://github.com/clarkevansteenderen/KG_watchlist_parallel/tree/main/.

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